AD-A052 626   MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF MECHANI--ETC F/G 20/4
PRESSURE DROP AND PHASE FRACTION IN OIL-WATER-AIR VERTICAL PIPE--ETC(U)
MAY 76 A R SHEAN

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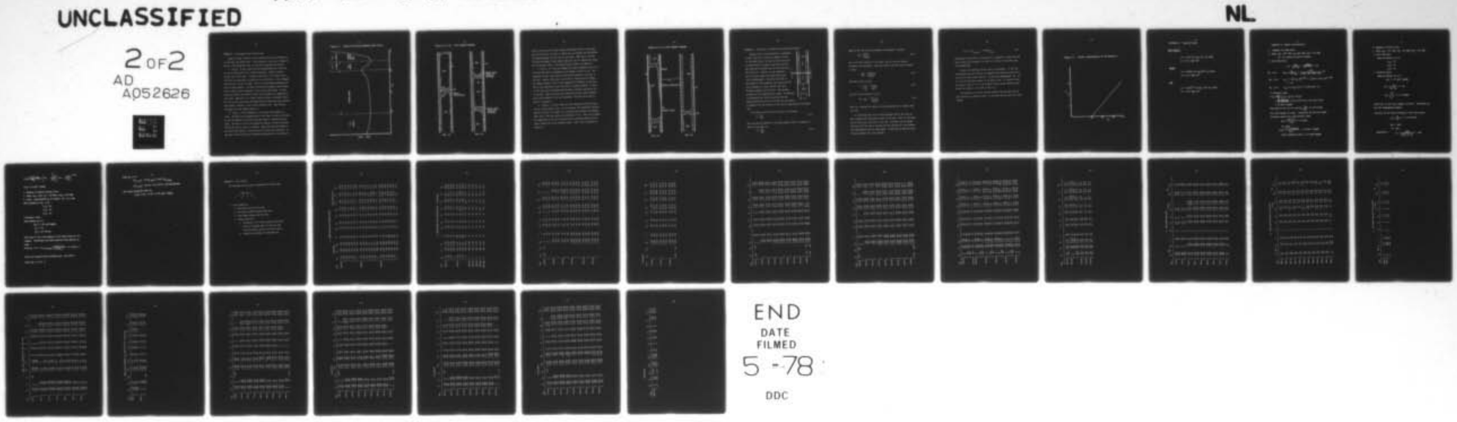

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APPENDIX C: Flow Regime Visual Observations.

Figure C1 shows a typical friction pressure loss curve disected into four main flow regime areas. The variation of this curve is keyed to Govier's flow regime map (Fig. 14) and can be explained as follows:

A. $0<F_o\leq a$: In this region the water predominates the fluid flow and can be characterized as a typical slug flow. Figure C2 shows a typical view of the tube. In region A the fluid is in counter flow around the air slugs while in region B the fluid flows at a rate commensurate with that of the air slugs. The oil is distributed throughout the water in small bubbles. At higher velocities the negative shear around the air slugs is small compared to that in the liquid slugs. As does Singh and Griffith the negative shear can be assumed to be neglected in most cases. When the oil in liquid volume fraction is increased from 0, the size of the liquid slugs decreases and the counterflow area thickens. This causes a decrease in the friction pressure loss. This decrease continues until the regime change at a.

B. $a<F_o<b$: At the transition a, the liquid flow changes to a froth. The water still predominates the flow (Fig. C3) next to the wall, but the oil bubbles in the water slug area begin to coalesce into oil slugs. The area A is still in counterflow, however in area B the water flow around the oil slugs in cocurrent. Hence the effective length of the water slugs begins to increase and the friction loss increases. As the water in the fluid slug is completely replaced by oil, the layer of

Figure C1. Typical Friction Pressure Loss Curve.

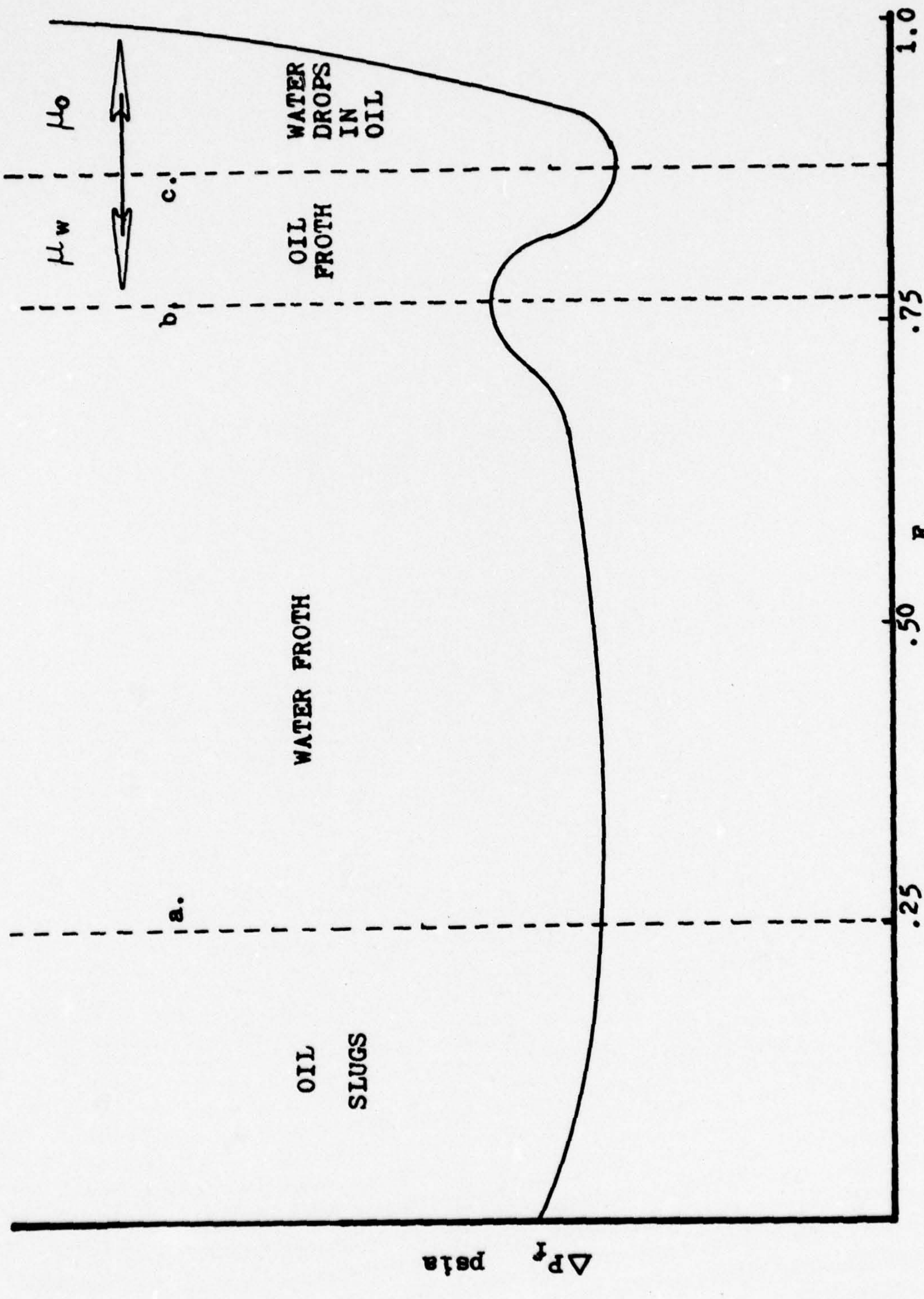


Figure C2 & C3. Flow Regime Diagram.

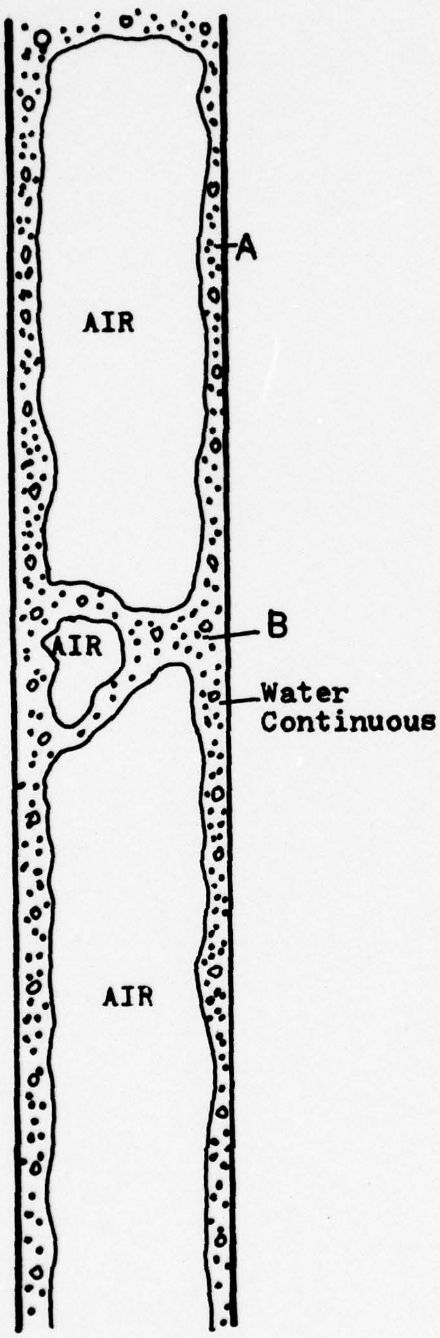


Fig. C2.

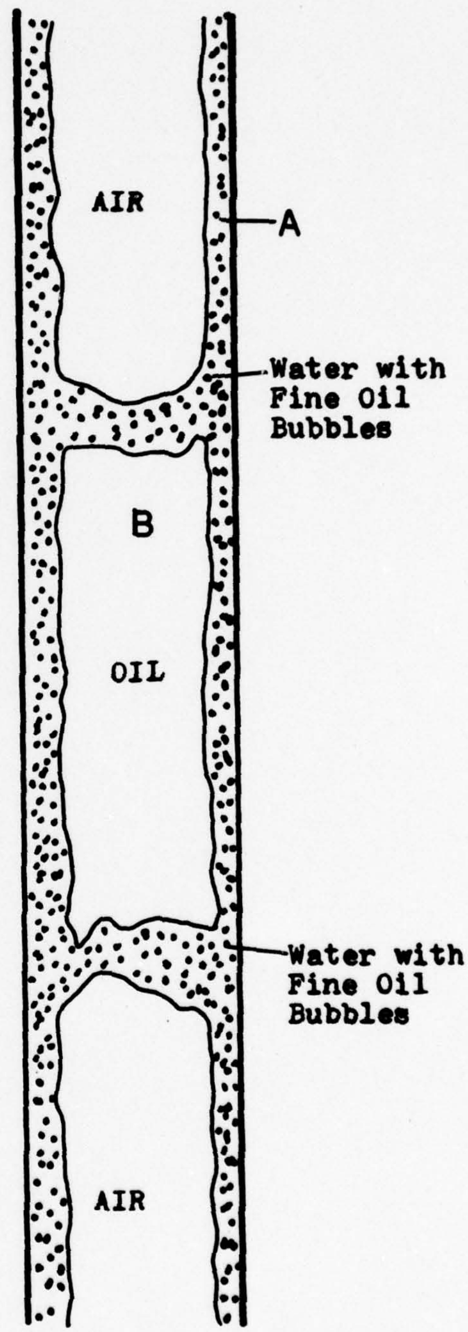


Fig. C3.

water on the tube wall becomes thinner and thinner until at the transition b the layer is too thin to contain any oil bubbles, and the bubbles are sheared between the wall and the air slugs. When this occurs the friction loss makes a sharp upward jump until the oil bubbles are forced out of the water layer. The pressure jump is point b on Figure C1.

C. $b<Fo<c$: At b the flow changes from water dominated froth to oil froth and the water is considered to be bubbles of water in oil. The exception is that a thin layer of water still persists on the wall of the tube. However, this layer is too thin to contain any oil bubbles. The laminar nature of the oil flow dampens the turbulence of the water and air and transition to pure slug flow is quickly achieved. At point c, full slug flow is achieved and the water is finally replaced by oil on the wall. When this occurs the counterflow friction loss dominated now by the viscosity of the oil, decreases. This dip can be seen at point c in Figure C1.

D. $c<Fo\leq 1.0$: In this region the flow transitions from pure slug flow to a quasi annular flow. As Fo increases, the counterflow velocity region (A in Fig. C5) reverses to co-current and increases in thickness while that of the slug region (B) decreases in size. After this reversal the combination of the oil viscosity and the increased upward velocity cause a sharp rise in the pressure losses. Again, this is apparent in Figure C1.

Figure C4 & C5. Flow Regime Diagram.

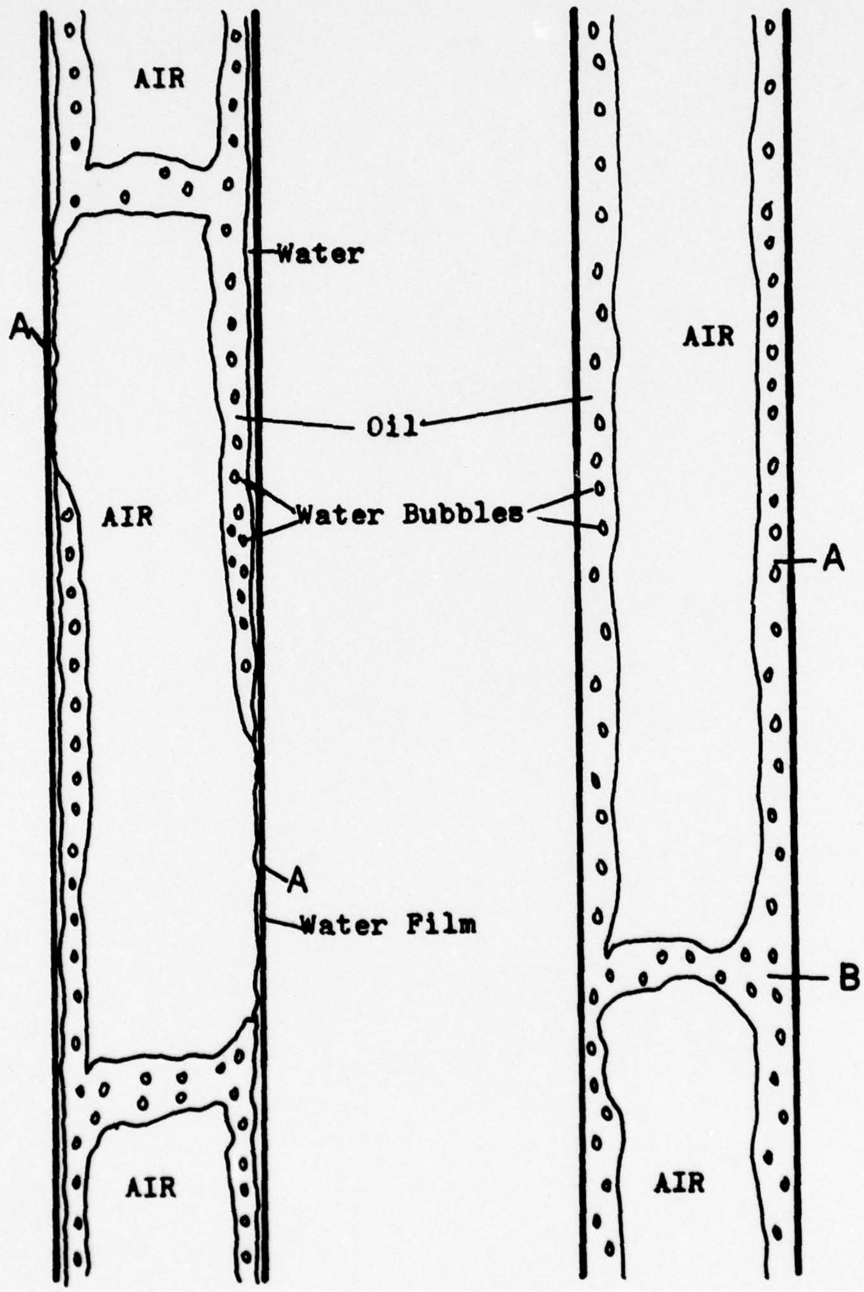


Fig. C4.

Fig. C5.

APPENDIX D: Derivation of Annular Flow Pressure Drop Method.

Annular flow is characterized by a continuous column of gas and a continuous annulus of fluid in co-current flow (A in Fig. D1) while slug flow is characterized by counter fluid flow over the gas slugs and co-current flow in the fluid slugs (B in Fig. D1). However, in the transition both co-current annulus and slug fluid flows occur simultaneously. Therefore the basis of this method is the assumption that transition flow can be modeled as a basic annular flow with a decreased annular fluid velocity. The decrease accounts for the remaining fluid slugs. In addition, in calculating the friction pressure loss the modified annular velocity of the fluid in the annulus is assumed to be the velocity of the fluid flowing alone in the entire tube.

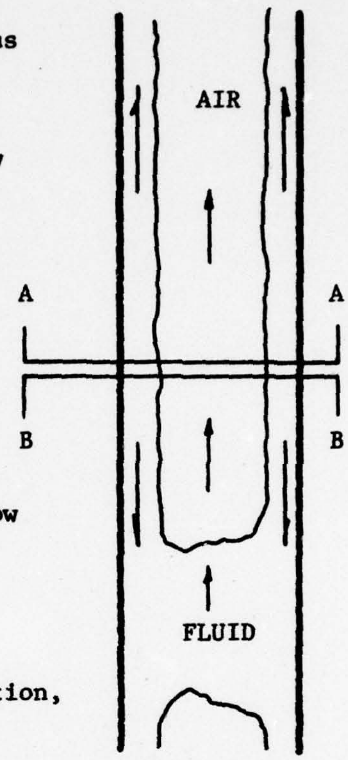


FIG. D1

From annular flow the fluid velocity is as follows:

$$\tilde{v}_f = \frac{Q_f}{A\alpha_f} \qquad \text{(D 1)}$$

This can then be modified for the Quasi-annular flow by a constant K, which is less than one.

$$\tilde{v}_f = \frac{KQ_f}{A\alpha_f} \qquad \text{(D 2)}$$

Based on this the following pressure loss analysis is derived:

$$Re_f = \frac{KQ_f D\rho_f}{A\alpha_f \mu_f g_o} \qquad \text{(D 3)}$$

Due to the high viscosity of the Nujol, the oil flow was laminar throughout the experiment. Hence the laminar friction factor equation is used.

$$f = \frac{16}{Re_f} = \frac{16A\alpha_f \mu_f g_o}{KQ_f D\rho_f} \qquad \text{(D 4)}$$

The shear stress is then:

$$\tau = \frac{f\rho v_f^2}{2g_o} = \frac{8\mu_f KQ_f}{A\alpha_f D} \qquad \text{(D 5)}$$

and the friction pressure loss is:

$$\Delta p_f = \frac{4\tau}{D} = \frac{32K\ \mu_f Q_f}{AD^2\alpha_f} \qquad \text{(D 6)}$$

which is a constant (K) times the loss associated with a complete annular flow.

In calculating the total friction pressure loss of the flow, we must recognize the transitional nature of the flow. That is, both annular and slug flows contribute to the loss. Therefore, we can assume that the total loss due to friction will be a portion of a full annular flow superimposed over the slug losses. We may then say that the total friction pressure loss is as follows:

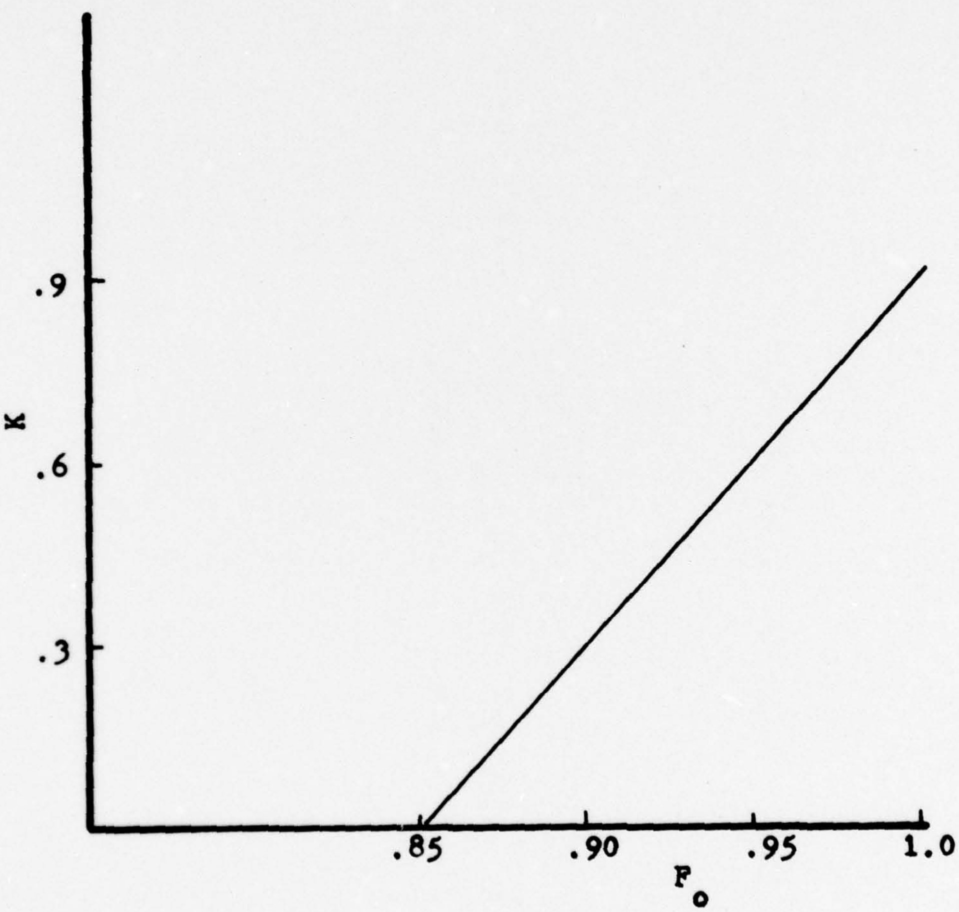
$$\Delta p_f = K \, \Delta p_{f_{annular}} + (1-K) \Delta p_{f_{slug}} \qquad \text{(D 7)}$$

The annular flow portion is calculated as in equation D 6 while the slug flow portion can be assumed to be that at Fo equal to zero where slug flow predominates.

Finally, the weighting factor K must be determined. In the flow investigated the quasi annular flow appeared only above the froth critical oil in liquid volume fraction. In this case approximately .85. Also, the flow was nearly annular at Fo equal to one. If, based on this, we assign a value of .9 to K at Fo equal to one, we may linearly interpolate the values of K as shown in Fig. D 2.

The values for the total friction pressure loss derived from the above analysis are shown in Table 3 of the main text and show very close results.

Figure D 2. Linear Interpolation of the Factor K.



APPENDIX E. Physical Data.

OIL(NUJOL)

μ = .0015 lb sec/ ft^2 at $100^\circ F$

ρ = 55.5 lbm/ ft^3

WATER

μ = .000015 lb sec/ft^2 at $100^\circ F$

ρ = 62.4 lbm/ ft^3

AIR

μ = 3.9×10^{-7} lb sec/ ft^2 at $100^\circ F$

ρ = .075 lbm/ ft^3

APPENDIX F. Sample Calculations.

A. Example of Slug Flow:

1. Data: Q_w= .282 CFM, Q_o=.094 CFM, Q_a= 1.82 CFM,

D= .75 inches, & L=74.25 inches.

2. Void Fraction:

$$F_o = \frac{Q_o}{Q_w + Q_o} = \frac{.094}{.282+.094} = .25$$

Eq. 5.10 $$\alpha_a = \frac{Q_a}{1.28\ Q_t} = \frac{1.82}{1.28(1.82+.282+.094)} = .65$$

Eq. 5.12 $$\alpha_o = 1.037\alpha_f F_o^{1.536} = 1.037(1-.65)(.25)^{1.536}$$
$$= .04$$

Eq. 5.14 $$\alpha_w = 1-(\alpha_a + \alpha_o) = 1-(.65+.04) = .31$$

3. Pressure Loss:

$$\Delta P_\rho = \frac{gL}{g_o}(\rho_w \alpha_w + \rho_o \alpha_o + \rho_a \alpha_a)$$
$$= \frac{32.2x74.25}{32.2x12x144}\ (55.5(.04)+62.4(.31)+.65(.075))$$
$$= .93 \text{ psi/ length}$$

From Fig.14 for F_o=.25 and $V_w = \dfrac{Q_w}{\alpha_f A}$ = 4.38 ft/sec the flow regime is slug. Therefore we use the Singh-Griffith method for the friction loss.

$$Re = \frac{\tilde{v}_m \rho_f D}{\mu_f} = 58,544.$$

f= .0051

$$\Delta P_f = \frac{2\ L\ f \rho_f \tilde{v}_m \alpha_w}{g_o D} = .58 \text{ psi/ length}$$

Total Pressure Loss = 1.51 psi/length

B. Example of Froth Flow:

1. Data: Q_w = .076 CFM, Q_o = .30 CFM, & Q_a = 1.82 CFM.

2. Void Fraction:

Same as method in A-2.

$$\alpha_a = .63$$
$$\alpha_w = .10$$
$$\alpha_o = .27$$

3. Pressure Loss:

Same as method in A-3.

$$\Delta P_\rho = .91 \text{ psi/ length}$$

$$F_o = \frac{Q_o}{Q_o + Q_w} = .80$$

$$V_w = \frac{Q_w}{\alpha_f A} = 1.11 \text{ ft/sec}$$

From fig. 14 the flow regime is froth. Therefore we use the homogeneous method.

Velocity of the fluid flowing in the tube alone:

$$f_o = \frac{Q_f}{A} = 2.04 \text{ ft/sec}$$

$$Re = 9387$$

$$f = .008$$

Quality(X):
$$X = \frac{\rho_a Q_a}{\rho_a Q_a + \rho_f Q_f} = .006$$

$$\Delta P_f = \frac{2f \rho_f \tilde{U}_{fo}}{D g_o} \left[1 + X \quad \frac{\rho_{fa}}{\rho_a} \right] \left[1 + X \quad \frac{\mu_{fa}}{\mu_a} \right]^{-1/4}$$

$\Delta P_f = .41$ psi/ length

C. Example of Quasi-Annular Flow:

1. Data: $Q_w = .019$, $Q_o = .36$ CFM, & $Q_a = 1.82$ CFM.

2. Void: Same Method as A2 except eq. 5.11 was used instead of eq. 5.10.

$$\alpha_a = .46$$

$$\alpha_w = .02$$

$$\alpha_o = .52$$

3. Pressure Loss:

Same method as A-3.

$$\Delta P_\rho = 1.30 \text{ psi/length}$$

$$F_o = .95$$

$$V_w = 5.16 \text{ ft/sec}$$

From fig.14 the flow regime is the water drop in oil regime. Therefore the quasi-annular flow method is used.

From eq. D 6: $\Delta P_{f \text{ annular}} = \dfrac{32 L \mu_f Q_f}{A D^2 \alpha_f} = 2.0$ psi/ L

From the Singh-Griffith Method $\Delta P_f = .712$ psi/L

From fig. D 2 K= .6

From eq. D 7:

$$\Delta P_{f\ tot} = K \Delta P_{f\ ann} + (1-K) \Delta P_{f\ slug}$$

$$\Delta P_{f\ tot} = .6(2.0) + .4(.712) = 1.48 \text{ psi/length}$$

The total pressure loss is:

$$\Delta P_t = 1.30 + 1.48 = 2.78 \text{ psi/ length}$$

APPENDIX G: Data Listing

The following code was used to designate the various runs:

```
        A 80- 10- 3
       /  /   \   \
      a   b    c   d
```

a. Test Disignation.

   A. Three Phase Void Fraction Test

   B. Two Phase Oil-Water Pressure Void Test

   C. Three Phase Pressure and Void Test

   D. Contact Angle Test

b. Introduced oil in liquid volume fraction (Fo)

c. Percent of maximum input air flow for test A and the mixture velocity for test B and C.

d. Identification number of individual run.

A. THREE PHASE VOID FRACTION DATA.

	Flow(CFM)							Velocity(ft/sec)			
Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A80-10-1	.134	.519	.333	92	.23	.50	.27	3.23	5.62	6.56	5.34
2	.134	.519	.333	94	.23	.52	.25	3.16	5.41	7.22	5.34
3	.134	.519	.333	94	.23	.51	.26	3.23	5.51	6.81	5.34
4	.134	.519	.309	98	.22	.52	.26	3.3	5.41	6.44	5.21
5	.134	.519	.309	98	.20	.55	.25	3.63	5.11	6.7	5.21
6	.134	.519	.309	98	.21	.53	.26	3.54	5.31	6.32	5.21
7	.1	.389	.348	87	.21	.45	.34	2.7	4.7	5.45	4.54
A80-20-1	.134	.519	.654	95	.18	.45	.38	4.15	6.39	9.28	7.11
2	.134	.519	.654	96	.18	.45	.37	4.03	6.25	9.65	7.11
3	.134	.519	.654	96	.18	.45	.37	4.03	6.25	9.65	7.11
4	.134	.519	.62	99	.16	.44	.40	4.54	6.39	8.4	6.9
5	.134	.519	.62	99	.18	.50	.32	4.13	5.62	10.34	6.9
6	.134	.589	.62	99	.18	.48	.34	4.03	5.86	9.88	6.9
7	.1	.389	.699	86	.14	.36	.50	3.8	5.9	7.5	6.44
A80-30-1	.134	.519	.983	97	.14	.45	.50	5.01	6.25	13.15	8.87
2	.134	.519	.983	98	.13	.38	.49	5.59	7.40	10.87	8.87
3	.134	.519	.983	98	.13	.32	.55	5.59	8.79	9.67	8.87
4	.134	.519	.929	100	.12	.48	.48	6.05	7.03	10.49	8.51
5	.134	.519	.929	101	.12	.38	.50	6.05	7.40	10.07	8.57
6	.134	.519	.929	101	.12	.43	.45	6.05	6.54	11.19	8.57
7	.1	.389	1.049	86	.13	.37	.50	4.3	5.7	11.3	8.33

A. THREE PHASE VOID FRACTION DATA. (Continued)

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A80-40-1	.134	.519	1.312	99	.09	.35	.56	8.07	8.04	12.7	10.65
2	.134	.519	1.312	99	.10	.34	.56	7.26	8.27	12.7	10.65
3	.134	.519	1.312	99	.09	.37	.54	8.07	7.60	13.17	10.65
4	.1	.389	1.399	86	.10	.36	.54	5.5	5.8	14.1	10.23
A80-50-1	.134	.519	1.64	100	.10	.41	.49	6.92	6.94	18.14	12.43
2	.134	.519	1.64	100	.07	.34	.59	10.37	8.27	15.06	12.43
3	.134	.519	1.64	100	.07	.41	.52	10.37	6.86	17.09	12.43
4	.1	.389	1.748	85	.07	.20	.73	8.0	10.8	12.9	12.12
A80-60-1	.1	.389	2.098	84	.07	.25	.68	8.0	8.4	16.7	14.02
A80-70-1	.1	.389	2.448	84	.07	.33	.60	8.0	6.4	21.9	15.92
A80-80-1	.1	.389	2.797	83	.07	.27	.66	8.0	7.8	22.9	17.81
A80-90-1	.1	.389	3.147	82	.05	.20	.75	11.7	10.4	22.7	19.7
A80-100-1	.1	.389	3.497	81	.06	.19	.75	9.8	11.1	25.10	21.6

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A75-0-1	.134	.40	0	91	.38	.62	0	1.91	3.50	0	2.89
2			0	91	.39	.61	0	1.86	3.55	0	2.89
3			0	91	.39	.61	0	1.86	3.55	0	2.89
A75-10-1			.353	93	.24	.45	.31	3.03	4.82	.617	4.81
2			.353	94	.25	.44	.31	2.90	4.93	.617	4.81
3			.353	96	.23	.46	.31	3.16	4.71	.617	4.81
A75-20-1			.707	97	.17	.37	.46	4.27	5.86	8.33	6.72
2			.707	97	.17	.45	.38	4.27	4.82	10.08	6.72
3			.707	98	.16	.38	.46	4.54	5.70	8.33	6.72
A75-30-1			1.060	100	.13	.39	.48	5.59	5.56	11.97	8.64
2			1.060	100	.15	.39	.46	4.84	5.56	12.49	8.64
3			1.049	101	.10	.35	.55	7.26	6.19	10.34	8.64
4			1.049	101	.10	.31	.59	7.26	6.99	9.63	8.64
A75-40-1			1.399	102	.09	.34	.56	8.07	6.38	13.54	10.47
2			1.399	102	.08	.29	.63	9.08	7.47	12.03	10.47
3			1.399	103	.09	.29	.62	8.07	7.47	12.23	10.47
A75-50-1			1.749	104	.08	.38	.54	9.08	5.70	17.55	12.37
2			1.749	103	.09	.33	.58	8.07	6.57	16.34	12.37
3			1.749	102	.08	.38	.54	9.08	5.70	17.55	12.37

Continued

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A75-60-1			2.099	103	.08	.38	.54	9.08	5.70	21.06	14.27
2			2.099	103	.07	.36	.57	10.37	6.02	19.96	14.27
3			2.099	103	.06	.34	.60	12.10	6.38	18.96	14.27
A75-70-1			2.449	104	.05	.29	.66	14.52	7.47	20.11	16.16
2			2.449	104	.06	.31	.63	12.10	6.99	21.07	16.16
3			2.449	104	.05	.31	.64	14.52	6.99	20.74	16.16
A75-80-1			2.798	104	.05	.32	.63	14.52	6.77	24.07	18.06
2			2.798	104	.04	.25	.71	18.15	8.67	21.36	18.06
3	.134	.40	2.798	105	.04	.30	.66	18.15	7.23	22.97	18.06

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_\omega$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A70-0-1	.179	.405	0	90	.43	.57	0	2.26	3.85	-	3.16
2			0	91	.43	.57	0	2.26	3.85	-	3.16
3			0	91	.43	.57	0	2.26	3.85	-	3.16
A70-10-1			.353	91	.29	.46	.25	3.34	4.77	7.65	5.08
2			.353	92	.28	.44	.28	3.46	4.99	6.83	5.08
3			.353	93	.31	.46	.23	3.13	4.77	8.32	5.08
A70-20-1			.698	94	.21	.34	.45	4.62	6.45	8.41	6.95
2			.703	94	.22	.39	.39	4.41	5.63	9.77	6.97
3			.703	94	.22	.33	.45	4.41	6.65	8.47	6.97
A70-30-1			1.055	95	.22	.33	.45	4.41	6.65	8.47	6.97
2			1.049	95	.15	.27	.58	6.47	8.13	9.79	8.84
3			1.048	96	.19	.30	.51	5.11	7.32	11.14	9.84
A70-40-1			1.406	96	.16	.30	.55	6.06	7.32	13.85	10.78
2			1.406	96	.18	.34	.48	5.39	6.45	15.87	10.78
3			1.397	96	.15	.32	.53	6.47	6.86	14.28	10.78
A70-50-1			1.746	96	.13	.27	.60	7.46	8.13	15.77	12.63
2			1.746	97	.14	.31	.55	6.93	7.08	17.20	12.63
3			1.746	97	.13	.32	.55	7.46	6.86	17.20	12.63
A70-60-1			2.095	97	.11	.29	.60	8.82	7.57	18.92	14.52
2			2.095	97	.12	.32	.56	8.08	6.86	20.27	14.52
3			2.095	97	.09	.23	.68	10.78	9.54	16.70	14.52
A70-70-1			2.444	98	.13	.27	.60	7.46	8.13	22.07	16.41
2			2.444	98	.11	.35	.55	8.82	6.27	24.08	16.41
3			2.444	98	.10	.31	.59	9.70	7.08	22.45	16.41
A70-80-1	.179	.405	2.794	98	.08	.23	.69	12.3	9.54	21.94	18.31
2			2.794	98	.08	.21	.70	12.3	10.45	21.63	18.31
3	.179	.405	2.794	99	.09	.38	.53	10.78	5.78	28.57	18.31

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_α	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A64-0-1	.224	.389	0	95	.43	.57	-	2.82	3.70	-	3.32
2			0	95	.45	.55	-	2.70	3.83	-	3.32
3			0	95	.47	.53	-	2.58	3.98	-	3.32
A64-10-1			.353	97	.32	.43	.25	3.79	4.90	7.65	5.23
2			.353	97	.30	.43	.27	4.05	4.90	7.08	5.23
3			.349	97	.30	.43	.27	4.05	4.90	7.00	5.21
A64-20-1			.698	98	.26	.38	.36	4.67	5.55	10.51	7.10
2			.698	98	.24	.36	.40	5.06	5.86	9.46	7.10
3			.703	98	.23	.37	.40	5.28	5.70	9.52	7.13
A64-30-1			1.055	98	.23	.33	.44	5.28	6.39	12.99	9.04
2			1.048	98	.23	.31	.46	5.28	6.8	12.35	9.00
3			1.048	99	.23	.31	.46	5.28	6.8	12.35	9.00
A64-40-1			1.397	100	.19	.27	.54	6.39	7.81	14.02	10.89
2			1.406	100	.18	.29	.53	6.74	7.27	14.38	10.94
3			1.397	100	.21	.32	.47	5.78	6.59	16.11	10.89
A64-50-1			1.746	100	.17	.27	.56	7.14	7.81	16.9	12.78
2			1.746	100	.20	.33	.47	6.07	6.39	20.13	12.78
3			1.746	100	.21	.32	.47	5.78	6.59	20.13	12.78
A64-60-1			2.095	100	.14	.26	.60	8.67	8.11	18.92	14.67
2			2.084	101	.18	.36	.46	6.74	5.86	24.55	14.62
3			2.084	101	.14	.26	.60	8.67	8.11	18.82	14.62
A64-70-1			2.432	102	.13	.26	.61	9.34	8.11	21.6	16.5
2			2.432	102	.14	.33	.53	8.67	6.39	24.87	16.5
3			2.432	102	.13	.24	.63	9.34	8.78	20.92	16.5
A64-80-1			2.779	103	.11	.24	.65	11.04	8.78	23.17	18.38
2			2.779	103	.16	.32	.52	7.59	6.59	28.96	18.38
3	.224	.389	2.779	103	.11	.31	.58	11.04	6.80	25.96	18.38

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A50-10-1	.2	.194	.349	79	.48	.16	.36	2.24	6.49	5.32	4.03
2	.2	.194	.349	79	.46	.19	.35	2.38	5.48	5.37	4.03
3	.2	.194	.349	81	.47	.17	.36	2.29	6.26	5.28	4.03
4	.267	.259	.35	83	.44	.23	.33	.33	6.1	5.8	4.75
5	.267	.259	.35	86	.42	.26	.32	3.4	5.4	5.9	4.75
A50-15-1	.267	.259	.52	86	.37	.24	.39	3.9	5.9	7.2	5.67
A50-20-1	.2	.194	.699	82	.34	.13	.53	3.16	8.21	7.15	5.92
2	.2	.194	.699	83	.36	.15	.49	3.03	7.20	7.65	5.92
3	.2	.194	.699	83	.33	.13	.54	3.31	7.85	7.03	5.92
4	.267	.259	.70	83	.33	.18	.49	4.3	7.6	7.8	6.64
5	.267	.259	.70	86	.31	.20	.49	4.7	6.9	7.7	6.64
A50-30-1	.2	.194	1.049	84	.31	.14	.55	3.52	7.51	10.34	7.82
2	.2	.194	1.044	85	.30	.13	.57	3.61	8.21	9.87	7.82
3	.2	.194	1.044	85	.29	.13	.58	3.78	8.41	9.65	7.82
4	.267	.259	1.05	82	.33	.18	.49	4.4	7.9	11.6	8.54
5	.267	.258	1.05	86	.27	.17	.56	5.3	8.2	10.3	8.54
A50-40-1	.2	.194	1.392	86	.27	.13	.60	4.01	7.85	12.68	9.68
2	.2	.194	1.392	87	.22	.11	.67	4.83	9.39	11.36	9.68
3	.2	.194	1.392	88	.26	.13	.61	4.14	8.41	12.29	9.68
4	.267	.259	1.40	82	.27	.14	.59	5.4	10.2	12.8	10.44
5	.267	.259	1.40	86	.29	.18	.52	5.0	7.8	14.2	10.44
A50-50-1	.2	.194	1.74	88	.26	.14	.60	4.18	7.51	15.69	11.56
2	.2	.194	1.74	89	.29	.16	.55	3.78	6.49	17.17	11.56
3	.2	.194	1.74	90	.26	.14	.60	4.25	7.51	15.61	11.56
4	.267	.259	1.75	81	.22	.12	.66	6.7	11.9	14.2	12.33
5	.267	.259	1.75	85	.28	.18	.54	5.2	7.8	17.6	12.33
A50-60-1	.2	.194	2.077	91	.22	.12	.66	5.04	9.14	16.80	13.39
2	.2	.194	2.077	92	.27	.15	.58	4.09	7.20	19.11	13.39
3	.2	.194	2.077	92	.21	.13	.66	5.26	8.03	16.95	13.39

Run	Q_w	Q_o	Q_a	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$	$\tilde{v}_m$
A50-60-4	.267	.259	2.11	80	.24	.14	.62	5.95	10.0	18.5	14.3
5	.267	.259	2.11	85	.28	.13	.64	6.2	11.2	17.7	14.3
A50-20-1	.2	.194	2.423	42	.19	.10	.71	5.62	10.51	18.57	15.27
2	.2	.194	2.423	42	.14	.09	.76	7.74	11.68	17.21	15.27
3	.2	.194	2.423	93	.23	.13	.64	4.71	7.85	20.65	15.27
4	.267	.259	2.46	79	.19	.09	.72	7.5	15.6	18.6	16.2
5	.267	.259	2.46	85	.19	.11	.70	7.6	12.5	19.0	16.2
A50-80-1	.267	.259	2.81	79	.24	.12	.64	6.1	11.6	23.7	18.1
2	.267	.259	2.81	84	.16	.08	.76	9.1	16.7	20.0	18.1
A50-90-1	.267	.259	3.16	78	.19	.09	.72	7.5	5.1	24.0	20.0
2	.267	.259	3.16	84	.15	.08	.77	9.6	18.7	22.0	20.0
A50-100-1	.267	.259	3.51	75	.21	.13	.61	5.5	10.7	31.3	21.9
2	.267	.259	3.51	84	.22	.12	.66	6.7	12.2	28.3	21.9

B. TWO PHASE FLOW DATA

Run	Q_w (CFM)	Q_o (CFM)	T	$\tilde{v}_m$	α_w	α_o	v_w (ft/sec)	v_o (ft/sec)	ΔP_T (Psi)	ΔP_f (Psi)
B0-3-1	.556	0	80	3	1.0	0	3.0	-	2.84	.16
2	.556	0	80	3	1.0	0	3.0	-	2.85	.17
3	.556	0	80	3	1.0	0	3.0	-	2.84	.16
B0-2-1	.368	0	80	2	1.0	0	2.0	-	2.77	.09
2	.368	0	80	2	1.0	0	2.0	-	2.77	.09
3	.368	0	80	2	1.0	0	2.0	-	2.77	.09
B25-3-1	.412	.130	84	3	.91	.09	2.46	7.85	2.78	.12
2	.412	.130	82	3	.93	.07	2.41	10.09	2.75	.09
3	.412	.130	84	3	.93	.07	2.3	10.09	2.77	.10
B25-2-1	.278	.092	88	2	.90	.10	1.68	5.0	2.69	.04
2	.278	.092	80	2	.92	.07	1.62	7.14	2.70	.04
3	.278	.092	80	2	.93	.07	1.62	7.14	2.70	.04
B50-3-1	.278	.276	85	3	.66	.34	2.29	4.41	2.69	.11
2	.278	.276	85	3	.66	.34	2.29	4.41	2.69	.11
3	.278	.276	85	2	.65	.35	2.32	4.28	2.69	.11
B50-2-1	.184	.184	87	2	.71	.29	1.41	3.45	2.62	.03
2	.184	.184	83	2	.72	.28	1.39	2.57	2.62	.03
3	.184	.184	88	2	.72	.28	1.39	3.57	2.64	.03
B75-2-1	.134	.415	85	3	.38	.62	1.92	3.68	2.61	.11
2	.134	.415	82	3	.37	.62	1.97	2.58	2.60	.10
3	.134	.415	86	3	.37	.63	1.97	2.58	2.62	.12
B75-2-1	.092	.276	87	2	.45	.55	1.11	2.73	2.53	.01
2	.092	.276	84	2	.48	.52	1.04	2.88	2.53	.001
3	.092	.276	86	2	.43	.57	1.16	2.63	2.53	.02
B80-3-1	.11	.44	80	3	.32	.68	1.87	3.53	2.55	.06
2	.11	.44	80	3	.31	.69	1.93	3.48	2.63	.15

B. TWO PHASE FLOW DATA (Continued)

Run	Q_w CFM	Q_o	T	v_m	α_w	α_o	v_w ft/sec	v_o ft/sec	ΔP_T Psi	ΔP_f Psi
B80-2-1	.07	.29	84	2	.35	.65	1.14	2.46	2.48	-.07
2	.07	.29	85	2	.35	.64	1.11	2.50	2.49	-.01
B80-1-1	.04	.15	82	1	.34	.66	.59	1.22	2.52	.03
2	.04	.15	85	1	.47	.53	.43	1.52	2.50	-.02
B85-3-1	.08	.47	91	3	.06	.94	7.05	2.71	4.07	1.67
2	.08	.47	90	3	.05	.95	9.0	2.68	4.13	1.72
B85-2-1	.06	.31	88	2	.20	.80	1.51	2.12	2.50	.06
2	.06	.31	90	2	.27	.73	1.21	2.33	2.47	-.001
B85-1-1	.03	.16	87	1	.32	.68	.47	1.25	2.59	.11
2	.03	.16	90	1	.43	.57	.35	1.50	2.48	-.03
B90-3-1	.06	.50	93	3	.05	.95	6.0	2.84	3.91	1.51
2	.06	.50	92	3	.04	.96	7.5	2.81	3.93	1.53
B90-2-1	.04	.33	91	2	.05	.95	3.31	1.91	3.30	.90
2	.04	.33	90	2	.06	.94	3.99	1.89	3.35	.95
B90-1-1	.02	.17	92	1	.11	.89	.90	1.01	2.56	.34
2	.02	.17	90	1	.10	.90	.99	1.0	2.56	.33
B95-3-1	.03	.52	83	3	.03	.97	5.03	2.93	4.18	1.79
2	.03	.52	93	3	.03	.97	5.03	2.93	3.98	1.59
B95-2-1	.02	.35	83	2	.04	.96	2.55	1.98	3.50	1.1
2	.02	.35	93	2	.06	.94	1.70	2.02	3.40	1.0
B95-1-1	.01	.18	82	1	.09	.91	.57	1.04	2.77	.36
2	.01	.18	93	1	.05	.95	1.02	1.00	2.81	.41
B100-3-1	0	.552	80	3	0	1.0	0	3.0	4.34	1.95
2	0	.552	80	3	0	1.0	0	3.0	4.31	1.92

B. TWO PHASE FLOW DATA (Continued)

Run	Q_w	CFM Q_o	T	$\tilde{v}_m$	α_w	α_o	ft/sec $\tilde{v}_w$	v_o	Psi AP_T	ΔP_f
B100-3-3	0	.552	80	3	0	1.0	0	3.0	4.34	1.96
B100-2-1	0	.368	80	2	0	1.0	0	2.0	3.55	1.16
2	0	.368	80	2	0	1.0	0	2.0	3.55	1.16
3	0	.368	80	2	0	1.0	0	2.0	3.57	1.18

C. THREE PHASE PRESSURE LOSS AND VOID TEST

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C0-4-1	.376	0	.364	1.825	-.04	70	.66	0	.34	3.07	-	5.92
2	.376	0		1.678	.008	71	.62	0	.38	3.28	-	5.24
3	.376	0		1.678	.008	71	.62	0	.38	3.28	-	5.24
4	.376	0		1.794	.156	64	.61	0	.39	3.34	-	5.08
C25-4-1	.282	.094		1.57	-.14	69	.51	.08	.36	2.69	6.81	5.57
2	.282	.094		1.57	-	86	.50	.10	.40	3.09	4.96	4.92
3	.282	.094		1.40	-.19	93	.50	.11	.39	3.08	4.82	4.99
4	.282	.099		1.609	.068	64	.53	.05	.42	2.87	10.86	4.71
C50-4-1	.188	.188		1.51	-.05	70	.44	.17	.39	2.34	6.19	4.96
2	.188	.188		1.60	.08	84	.37	.22	.41	2.78	4.56	4.85
3	.188	.188		1.40	-.18	91	.38	.23	.38	2.67	4.36	5.16
4	.188	.188		1.516	.015	66	.41	.17	.42	2.52	5.87	4.70
C75-4-1	.094	.282		.54	-1.04	72	.28	.35	.37	1.82	4.43	5.29
2	.094	.282		1.51	-	80	.22	.41	.37	2.31	3.75	5.33
3	.094	.282		1.45	-.18	88	.22	.43	.35	2.28	3.56	5.71
4	.094	.282		1.424	-.118	66	.24	.38	.38	2.15	4.03	5.16
C80-4-1	.076	.300		.45	-.94	74	.17	.39	.44	2.37	4.22	4.49
2	.076	.300		1.53	.13	78	.16	.41	.43	2.65	3.96	4.57
3	.076	.300		1.55	.11	87	.15	.44	.41	2.75	3.74	4.78
4	.076	.300		1.365	.025	67	.16	.38	.46	2.55	4.29	4.32
C85-4-1	.056	.32		.52	-.86	76	.13	.44	.43	2.43	3.99	4.50
2	.056	.32		1.36	.09	76	.11	.39	.50	2.87	4.47	3.92
3	.056	.32		1.36	-.14	86	.11	.50	.4	2.72	3.46	5.12
4	.056	.32		1.351	-.04	68	.13	.44	.43	2.32	3.99	4.57
C90-4-1	.038	.34		.39	-.92	78	.09	.45	.46	2.37	4.09	4.29
2	.038	.34		1.16	-.1	75	.07	.45	.48	2.99	4.09	4.13
3	.038	.34		1.213	-.04	86	.08	.55	.37	2.75	3.35	5.29
4	.038	.34		1.213	-.04	70	.08	.44	.48	2.75	4.18	4.09

C. THREE PHASE PRESSURE LOSS AND VOID TEST (Continued)

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C95-4-1	.019	.36		1.43	-.35	99	.03	.72	.25	4.13	2.73	7.66
2	.019	.36		1.93	.31	75	.04	.63	.33	2.35	3.11	6.05
3	.019	.36		2.11	.45	86	.03	.67	.30	4.13	2.92	6.48
4	.019	.36		1.529	.175	71	.04	.53	.43	2.79	3.72	4.52
C100-4-1	0	.376		2.622	.48	70	0	.75	.25	-	2.71	8.04
2	0	.376		2.475	.69	70	0	.75	.25	-	2.73	7.85
3	0	.376		2.475	.69	71	0	.75	.25	-	2.73	7.85
4	0	.376	.364	2.626	.83	71	0	.75	.25	-	2.71	8.04

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C0-8-1	.376	0	1.092	1.509	.389	64	.42	0	.58	4.90	-	10.17
2	.376	0		1.455	.235	73	.46	0	.54	4.49	-	10.88
3	.376	0		1.476	.416	80	.40	0	.60	5.17	-	9.80
C25-8-1	.282	.094		.785	-.32	64	.41	.04	.55	3.78	13.8	10.63
2	.282	.094		1.176	.026	73	.37	.06	.56	4.10	8.24	10.52
3	.282	.094		1.194	.254	80	.31	.05	.64	5.02	9.63	9.24
C50-8-1	.188	.188		.025	-.665	66	.25	.09	.66	4.60	10.98	9.01
2	.188	.188		1.244	.114	74	.29	.15	.56	3.52	16.99	10.52
3	.188	.188		1.353	.173	80	.29	.17	.54	3.52	5.97	11.07
C75-8-1	.094	.282		.107	-.813	68	.17	.20	.63	3.04	7.70	9.37
2	.094	.282		1.261	.111	75	.18	.28	.54	2.82	5.47	11.01
3	.094	.282		1.426	.196	80	.17	.32	.51	2.93	4.77	11.75
C80-8-1	.076	.300		.094	-1.086	70	.16	.31	.53	2.55	5.22	11.28
2	.076	.300		1.257	.197	77	.13	.30	.57	3.23	5.40	10.41
3	.076	.300		1.273	.413	82	.09	.26	.65	4.75	5.43	9.11
C85-8-1	.056	.32		-.18	-1.24	70	.10	.33	.57	3.04	5.27	10.41
2	.056	.32		.915	.085	78	.06	.28	.66	4.91	6.21	9.01
3	.056	.32		1.108	.068	83	.05	.38	.57	5.74	4.61	10.41
C90-8-1	.038	.34		-.195	-1.135	71	.06	.33	.61	3.69	5.60	9.68
2	.038	.34		1.115	-.145	78	.04	.48	.48	4.69	3.87	12.38
3	.038	.34		1.274	.144	83	.04	.42	.53	4.69	4.36	11.15
C95-8-1	.019	.36		1.121	-.049	72	.1	.48	.51	8.60	4.10	11.61
2	.019	.36		2.663	1.423	79	.1	.51	.48	8.60	3.87	12.28
3	.019	.36		2.535	1.215	83	.1	.54	.45	8.60	3.61	13.30
C100-8-1	0	.376		1.962	.502	72	0	.61	.39	-	3.35	15.21
2	0	.376		3.187	1.657	79	0	.64	.36	-	3.18	16.57
3	0	.376	1.092	2.983	1.543	84	0	.60	.40	-	3.38	14.98

(Continued)

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C0-16-1	.376	0	2.548	1.544	.968	85	.22	0	.78	9.50	0	17.63
2	.376	0		1.534	.850	88	.26	0	.74	8.01	0	18.58
3	.376	0		1.536	.794	.76	.28	0	.72	7.37	0	19.14
C25-16-1	.282	.094		1.405	.738	85	.22	.03	.75	6.84	18.24	18.50
2	.282	.094		1.440	.802	88	.20	.04	.76	7.70	11.60	18.28
3	.882	.094		1.313	.825	76	.20	.03	.77	7.70	20.4	17.84
C50-16-1	.188	.188		1.404	.597	85	.19	.12	.69	5.29	8.37	20.21
2	.188	.188		1.494	.727	88	.18	.12	.70	5.64	8.65	19.74
	.188	.188		1.28	.709	76	.17	.11	.72	5.97	9.63	19.14
C75-16-1	.094	.282		1.747	.774	85	.10	.30	.60	5.11	5.18	22.92
2	.094	.282		1.794	.775	88	.13	.29	.58	4.08	7.44	19.94
3	.094	.282		1.5	.892	77	.10	.21	.69	5.11	7.44	19.94
C80-16-1	.076	.30		1.281	1544	87	.08	.22	.70	5.10	7.48	19.74
2	.076	.30		1.391	.482	90	.05	.32	.63	7.79	5.08	22.11
3	.076	.30		1.61	1.01	78	.07	.23	.70	5.73	6.96	19.94
C85-16-1	.056	.32		1.356	.421	88	.04	.34	.62	6.91	5.07	22.58
2	.056	.32		1.518	.824	90	.04	.25	.71	7.60	7.07	19.38
3	.056	.32		1.316	.71	80	.04	.27	.69	8.22	6.34	20.09
C90-16-1	.038	.34		1.647	.658	88	.03	.39	.59	8.26	4.78	23.50
2	.038	.34		2.035	1.274	80	.03	.39	.58	8.26	4.70	23.78
3	.038	.34		1.72	1.12	80	.03	.29	.68	8.26	6.44	20.12
C95-16-1	.019	.36		2.828	1.769	88	.01	.43	.56	8.60	4.54	24.80
2	.019	.36		3.047	1.809	90	.01	.51	.48	8.60	3.87	28.66
3	.019	.36		2.783	1.636	80	.01	.59	.40	8.60	3.34	34.43
C100-16-1	0	.376		3.031	1.223	88	-	.55	.45	-	3.73	30.62
2	0	.376		3.201	2.062	90	-	.48	.52	-	4.28	26.46
3	0	.376	2.548	3.306	2.231	80	-	.56	.44	-	3.64	31.53

(Continued)

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C0-12-1	.376	0	1.82	1.470	.768	73	.26	0	.74	7.8	-	13.4
2	.376	0		1.379	.677	74	.26	0	.74	7.8	-	13.4
3	.376	0		1.430	.428	84	.37	0	.63	5.46	-	15.79
C25-12-1	.282	.094		1.352	.395	74	.32	.04	.64	4.73	13.8	15.47
2	.282	.094		1.411	.543	75	.32	.03	.65	4.73	16.47	15.33
3	.282	.094		1.403	.588	84	.25	.06	.69	6.15	8.24	14.35
C50-12-1	.188	.188		1.449	.455	75	.27	.11	.62	3.73	9.37	16.02
2	.188	.188		1.499	.451	76	.27	.13	.60	3.73	7.80	16.62
3	.188	.188		1.465	.409	84	.26	.16	.58	4.00	6.55	16.78
C75-12-1	.094	.282		1.522	.471	78	.19	.23	.58	2.73	6.63	16.99
2	.094	.282		1.208	.598	76	.19	.26	.56	2.73	6.01	17.72
3	.094	.282		1.618	.522	85	.14	.30	.56	3.65	5.87	17.72
C80-12-1	.076	.30		1.484	.718	80	.08	.23	.69	5.10	7.05	14.37
2	.076	.30		1.630	.609	78	.08	.37	.55	5.10	4.39	18.38
3	.076	.30		1.276	.335	85	.12	.26	.62	3.50	6.22	15.95
C85-12-1	.056	.32		1.137	.502	81	.04	.22	.74	8.22	7.76	13.38
2	.056	.32		1.200	.441	80	.04	.27	.69	8.22	6.34	14.35
3	.056	.32		1.302	.281	86	.04	.39	.57	8.22	4.50	17.13
C90-12-1	.038	.34		1.392	.722	82	.03	.22	.75	8.26	8.25	13.62
2	.038	.34		1.332	.539	80	.03	.28	.69	8.26	6.67	14.67
3	.038	.34		1.639	.607	86	.03	.38	.59	8.26	4.86	17.28
C95-12-1	.019	.36		2.572	1.238	82	.01	.54	.45	8.60	3.61	22.17
2	.019	.36		2.645	1.254	81	.01	.56	.43	8.60	3.49	23.15
3	.019	.36		2.745	1.466	86	.01	.52	.47	8.60	3.74	21.26
C100-12-1	0	.376		3.040	1.820	82	0	.51	.49	-	4.00	20.22
2	0	.376		3.161	1.869	81	0	.54	.46	-	3.77	21.59
3	0	.376	1.82	3.089	1.810	86	0	.54	.46	-	3.81	21.30

(Continued)

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C0-20-1	.376	0	3.276	1.654	1.000	74	.23	0	.77	8.73	-	23.23
2	.376	0		1.166	.590	72	.22	0	.78	9.50	-	22.67
3	.376	0		1.682	1.149	78	.20	0	.80	10.26	-	22.22
C25-20-1	.282	.094		1.437	.577	74	.29	.03	.88	5.23	16.47	26.32
2	.282	.094		1.514	.731	73	.26	.03	.71	5.85	15.02	25.28
3	.282	.094		1.408	.682	78	.24	.03	.73	6.30	16.47	24.51
C50-20-1	.188	.188		1.365	.601	75	.20	.10	.70	5.13	10.53	25.28
2	.188	.188		1.488	.638	74	.21	.12	.67	4.82	8.65	26.56
3	.188	.188		1.546	1.050	78	.12	.07	.81	8.44	13.99	22.05
C75-20-1	.094	.282		1.494	.843	76	.09	.17	.74	5.49	9.12	24.08
2	.094	.282		1.663	1.020	76	.11	.15	.74	4.82	10.21	23.92
3	.094	.282		1.763	1.063	80	.09	.20	.71	5.87	7.82	24.82
C80-20-1	.076	.30		1.437	.585	76	.09	.26	.65	4.75	6.29	27.21
2	.076	.30		1.454	.583	77	.08	.27	.65	5.10	5.95	27.59
3	.076	.30		1.543	.763	80	.08	.24	.68	5.50	6.71	26.09
C80-20-1	.076	.30		1.437	.585	76	.09	.26	.65	4.75	6.29	27.21
2	.076	.30		1.454	.583	77	.08	.27	.65	5.10	5.95	27.59
3	.076	.30		1.543	.763	80	.08	.24	.68	5.50	6.71	26.09
C85-20-1	.056	.32		1.189	.642	78	.04	.18	.78	7.60	9.45	22.93
2	.056	.32		1.412	.204	78	.05	.24	.71	5.74	7.33	25.06
3	.056	.32		1.510	.900	82	.04	.23	.73	6.91	7.52	24.55
C90-20-1	.038	.34		1.691	.697	78	.03	.39	.58	8.26	4.75	30.37
2	.038	.34		2.058	1.171	78	.04	.33	.63	5.58	5.60	28.11
3	.038	.34		2.134	1.279	82	.03	.33	.64	8.26	5.60	27.59
C95-20-1	.019	.36		3.108	2.095	79	.01	.41	.58	8.60	4.76	30.84
2	.019	.36		3.430	2.237	78	.01	.49	.50	8.60	4.02	35.45
3	.019	.36		3.283	1.885	82	.01	.51	.42	8.60	3.41	42.88

(Continued)

Run	Q_w	Q_o	Q_a	ΔP_T	ΔP_f	T	α_w	α_o	α_a	$\tilde{v}_w$	$\tilde{v}_o$	$\tilde{v}_a$
C100-20-1	0	.376	3.276	3.324	2.126	79	0	.50	.50	0	4.07	35.73
2	0	.376		3.527	2.281	79	0	.52	.48	0	3.91	37.31
3	0	.376	3.276	3.595	2.408	82	0	.50	.50	0	4.10	35.45